Reduction and analysis of one-way laser ranging data from ILRS ground stations to LRO

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ABSTRACT

One-way LR (Laser Ranging) is being performed routinely from ILRS (International Laser Ranging Service) ground stations to LOLA (Lunar Orbiter Laser Altimeter), onboard NASA's LRO (Lunar Reconnaissance Orbiter). From the accurate range measurements, spacecraft orbits and parameters of the lunar gravity field can be modeled. Furthermore, the data can be used for monitoring the long-term behavior of the LRO clock and for precisely referencing the MET (Mission Elapsed Time) to TDB (Barycentric Dynamical Time). We present the current status of our effort to process, analyze and use selected LR data for LRO clock characterization, orbit determination and gravity field estimation.

INTRODUCTION

Satellite LR has been used to track Earth satellites since 1964 and has reached an accuracy of a few millimeters nowadays. The high-precision positioning enables the development of greatly improved Earth gravity field models and provides constraints for fundamental physics [1]. For the LRO mission LR supports the development of accurate spacecraft orbits and a global lunar geodetic grid [2], which will be the basis for future lunar exploration missions [3]. In addition, LR was used for keeping track of the time drift of the LRO USO (Ultra Stable Oscillator) with respect to ground station clocks, and thereby confirmed the long-term stability that has been estimated in preflight ground tests. LR thereby enables a referencing of the LRO MET to ground time with higher precision than provided by standard techniques, which are accurate to only 3 ms [4].

EXPERIMENT

The basic principle of LR to LRO is shown in Fig. 1. Ranging is performed from a ground station that fires a laser pulse to LRO at a certain time. A received pulse is time stamped by the LOLA instrument at the satellite. By calculating the light travel time between the receiving and the firing time, it is possible to derive a high-precision range measurement with a RMS of 10 to 30 cm [4]. An optical receiver is attached to the HGA (High Gain Antenna), which is always pointed towards Earth and incoming Earth range pulses are transmitted into the LOLA laser detector by a fiber optic cable. This permits LR tracking of LRO simultaneously while LOLA is ranging to the lunar surface [3].

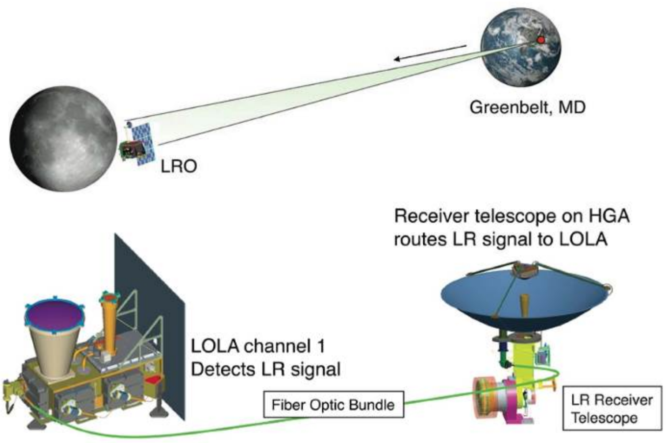

Fig. 1: LR to LRO - basic principle [3]

Table 1: Wettzell LR to LRO pass dates

Pass	Begin	End
Tue 15th Nov 2011	*1:49 am CET*	*2:24 am CET*
Wed 16th Nov 2011	*4:02 am CET*	*4:37 am CET*

SHOT MATCHING

The range measurement is derived from a firing event at the station and a receiving event at the satellite, which are stored separately on ground or on the spacecraft, respectively. The laser fire times are written to CDR (Consolidated Laser Ranging Data Format) files by the station during an observation of LRO and then sent to GSFC (Goddard Space Flight Center) for processing. The LOLA laser receive times are downlinked from LRO to Earth, and, for example, provided at the LOLA PDS (Planetary Data System) data node (http://imbrium.mit.edu/). To retrieve a range measurement, we pair a station laser firing time from the CDR file with the corresponding LOLA laser receive time taken from the RDR (Reduced Data Records) files. This process will be called "matching" in the following and is shown in Fig. 2 schematically.
We started with the analysis of the data recorded from "Fundamentalstation Wettzell" located in South Germany during two LR to LRO ranging campaigns (Table 1). We used nominal spacecraft navigation data to calculate the laser travel time for given station laser fire time. The software toolkit SPICE from NAIF (Navigation and Ancillary Information Facility) is used to carry out the relevant geometric transformations [2]. Receiving events that are close enough to the prediction, can be referenced to the corresponding fire event. Since LOLA is running at 28 Hz (with a mean Δt of 0.0357s between receiving events), the accuracy of the spacecraft position with approximately 12 m [2] is more than sufficient to relate firing and receiving events.
Due to the impulse response of the LOLA detector electronics, received laser pulses are distorted as a function of energy which causes a shift in the receive time [5]. An empirical station range walk correction is applied as presented in [6] during the processing of the RDR files for correcting this. Therefore individual station values were estimated from the processing of many passes as it will be shown later in the text.
The results of the matching for the pass of the 15th November 2011 are shown in Fig. 3-7. Fig. 3 shows the predicted light time from SPICE and the light time of the actual matched shots in seconds on the left and km on the right axis. The difference between prediction and matched shots is plotted in Fig. 4. Fig. 5 shows the deviation of the matched shots with respect to a linear fit and Fig. 6 with respect to a 4th order polynomial fit. Within Fig. 6 one can see the accuracy of the LR to LRO measurements by looking at the variation (RMS of 9.9 cm during the 35 minutes pass). This is consistent with the design specification for the timing accuracy of 0.5 ns (= 15 cm) for LOLA [5]
Due to timing issues of the Wettzell laser, which have been resolved by now, the fire frequency could not be synchronized with the LOLA frequency exactly. Consequently not all gates for ranges from Earth were hit and data gaps as well as grouping of the matched shots are observed [J. Eckl, personal communication]. The ratio of shots that could be matched to the total number of fired shots from the station is about 12.2% for that pass. The loss of signal is caused by the acquisition and tracking of the satellite in combination with a feedback delay for the station operator whether s/he hit LRO. Furthermore, the laser fire times have to be synchronized with the LOLA Earth range gate, which is open for $\approx$ 8 ms at a 28 Hz frequency. During this pass the fire frequency was set to $\approx$ 14 Hz since the local laser is only capable of firing with up to 20 Hz at the needed energy level.
The root mean square (RMS) of the measurement may be used to assess the quality of the matches for single or large number of passes (see later in text). As will be shown later in the text, relativistic effects (variation in velocity with respect to the solar system barycenter and gravitational potential at LRO) may explain the offset of $\approx$ 160.3 km, the drift of $\approx$ 440 m, and the parabola deviation ($\approx 2\cdot10^{-13}$ s/s^2) with respect to the linear fit.

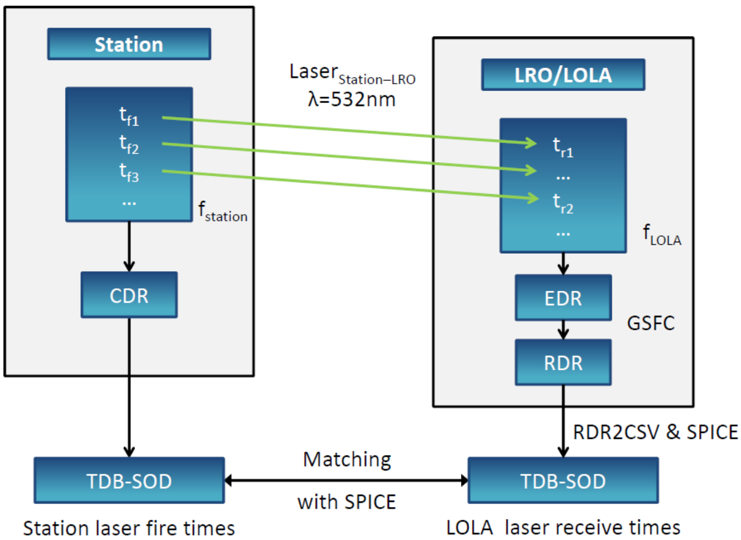

Fig. 2: Matching procedure

DATA PROCESSING

A program was developed to match a large number of passes automatically. Currently public data (May 2013) from commissioning phase, nominal mission 01 to 13, science mission 01 to 26 as well as extended science mission 01 to 03 have been processed [1]. There is a total number of ≈ 8300 observation passes retrieved from the station laser fire time files, from which ≈ 5430 were selected for processing. Passes that contain erroneous data or missing flags in either the firing or the receiving times were discarded. Also passes that contain ranging data from multiple stations were not evaluated. For identifying successful passes the following two quality criteria were used: measurement variation RMS < 50 cm, ratio of matched to fired shots > 1 %. About 3260 passes were matched successfully and cover a time span of 1240 days with an overall mean measurement RMS of 13.2 cm. Fig. 7 shows measurement RMS values in seconds, and Fig. 8 shows the ratio of matched-to-fired shots over days since the Jan 1st 2009 for successfully processed passes. The colors indicate the various stations that carry out the ranging. Note that the high RMS (≈ 20 cm) for the GO1L station is due to the wider pulse of the laser that is used for the LR to LRO [J. McGarry, personal communication] [2]. However, GO1L usually has more matched shots than other stations due to its capability of firing synchronized at 28 Hz to LOLA.
The processed data is used in various applications, among others for estimating the range walk correction values for each station. Data from several passes were used to yield an optimum mean value to correct the receiving times of distorted pulses. Furthermore, an accurate conversion of MET to TDB is important for a successful application due to the 1-way architecture of the LRO-LR experiment. The drift and the aging describe the behavior of the clock rate over time, which is changing due to clock errors, external influences, relativistic effects and temperature variations as well as other effects as outgassing.

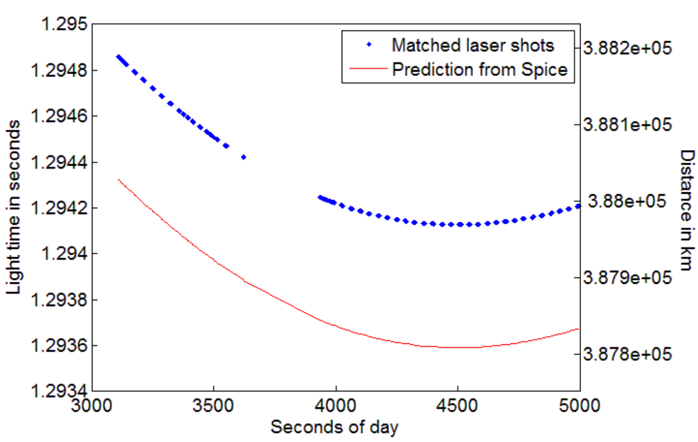

Fig. 3: Prediction and matches

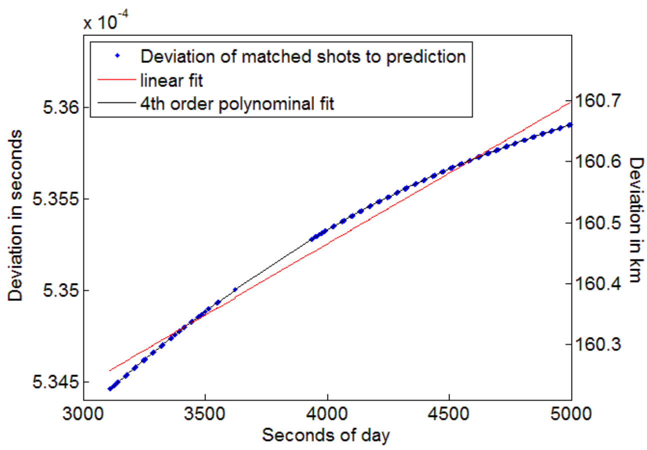

Fig. 4: Deviation of matched shots to prediction

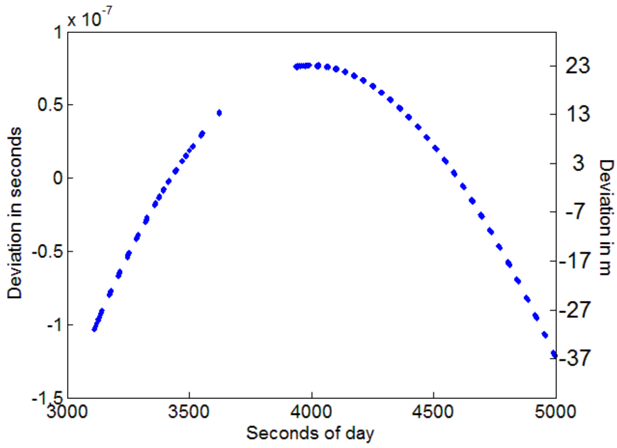

Fig. 5: Deviation of matched shots to linear fit

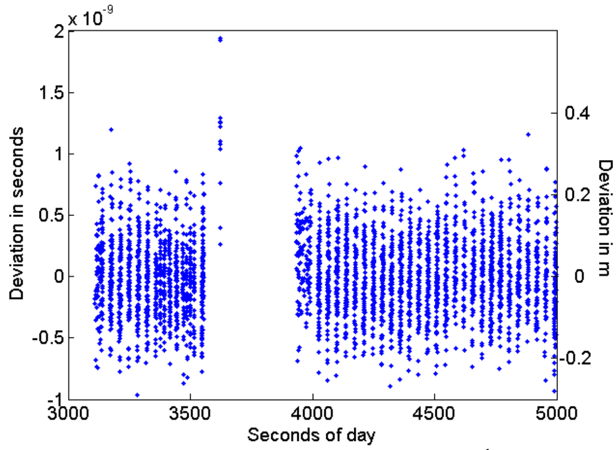

Fig. 6: Deviation of matched shots to 4th order fit

[1] Commissioning phase as well as nominal, science and extended science mission denote the various mission phases. These phases are again subdivided and numbered in order.
[2] GO1L is the 4-letter code for the NGSLR (Next Generation Satellite Laser Ranging) station located at GSFC.

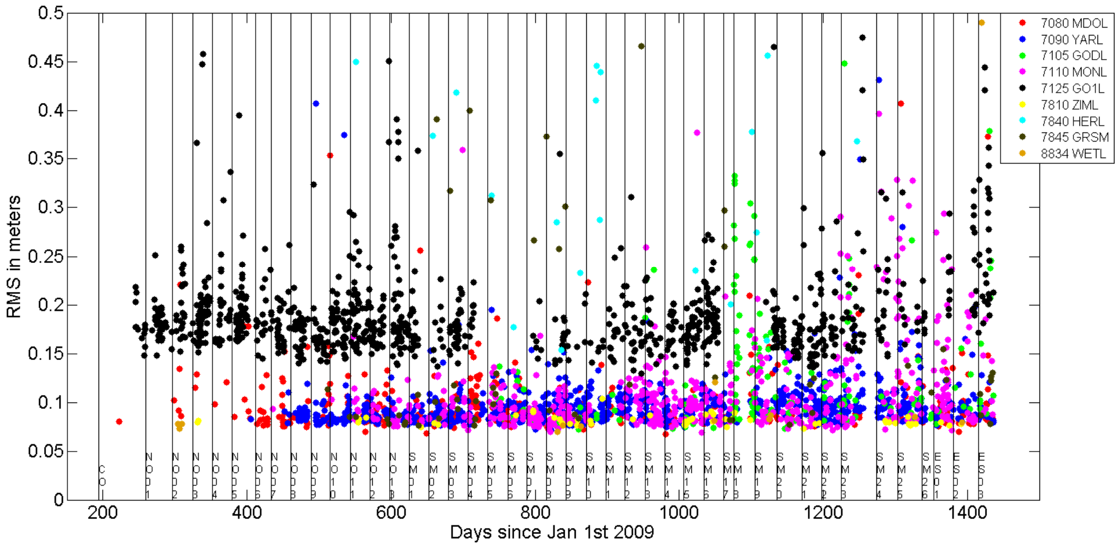

Fig. 7: Pass measurement RMS

Fig. 9 shows the drift values for the LRO clock for the year 2010 with respect to TDB estimated from the processed passes in days since Jan 1st 2009. The drift values were evaluated pass by pass and the trajectory kept fixed by using nominal navigation data. Note the mean linear trend in the satellite clock rate, which represents the aging. Since the time system used is TDB, one can see variations due to relativistic effects with a period of 365 days (Earth-Moon orbit around the sun) and 28 days (Moon orbit around the Earth). Variations that are on top of this are due to the LRO orbit that has a period of ≈ 120 minutes.
For the conversion of MET to ground times used during the generation of the RDR files, we use a long-term approximation for the satellite clock that is not including variations due to relativity with respect to TDB in particular. Therefore deviations with respect to the predictions emerge as offset, drift and parabola shaped deviation as shown in Fig. 4 and Fig. 5. From the long-term drift a mean aging value of $4.6\mathrm{x}10^{-17}$ s/s^2 can be estimated which is at the same order of magnitude as the aging values estimated previously [4]. Currently the theoretical modeling of the LRO clock is in progress in order to calculate and correct influences due to relativity as well as other effects on the LRO clock. By being able to model the clock behavior better, the conversion of MET to TDB and the deviations of the matches with respect to the predictions are expected to improve. Once the modeling and the understanding are improved we expect that a successful application of the LRO LR data to orbit determination should be feasible.

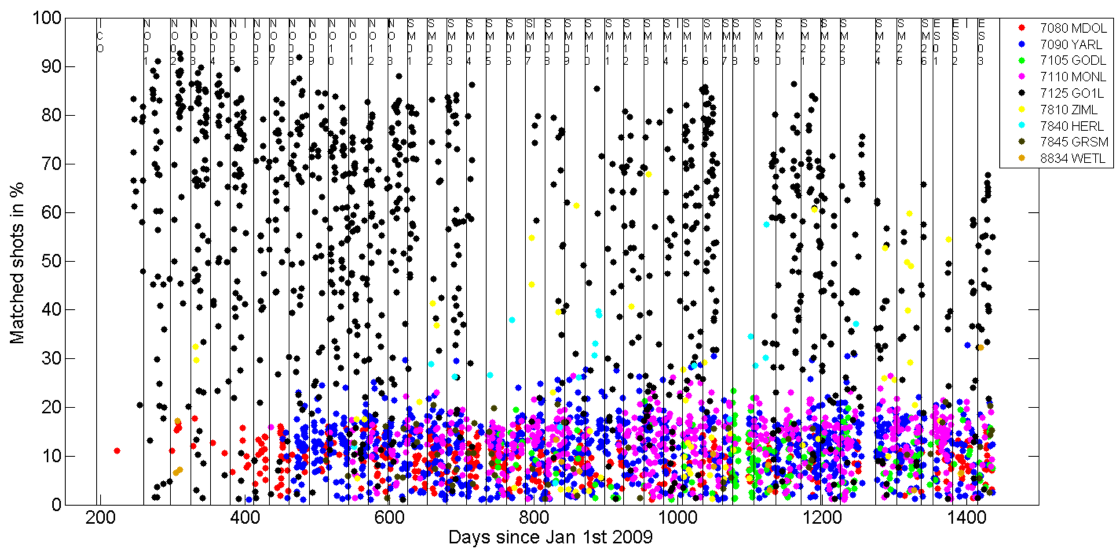

Fig. 8: Pass ratio of matched to fired shots

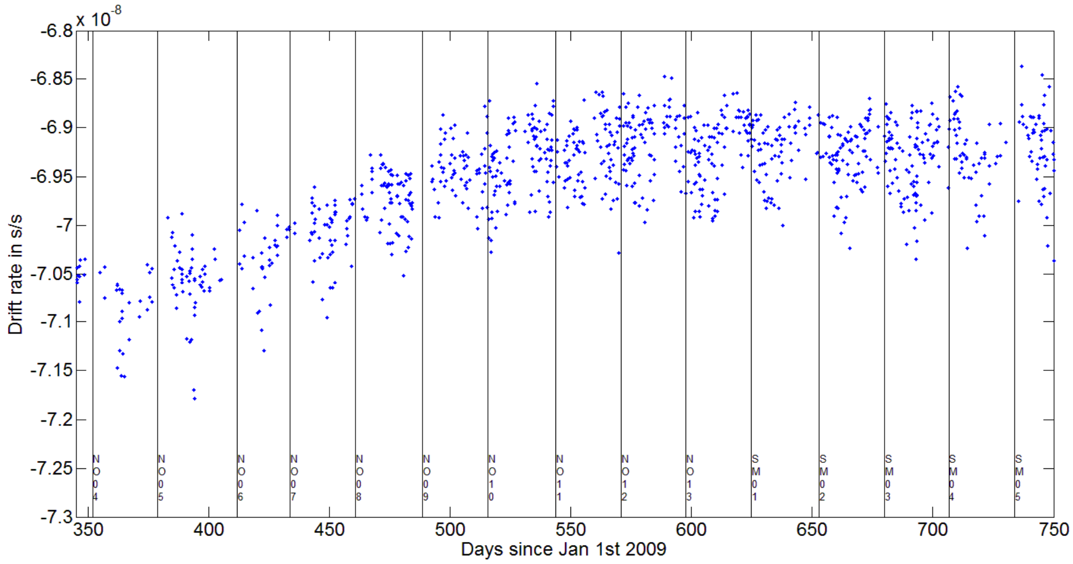

Fig. 9: Pass LRO clock drift estimated for the year 2010

STATUS AND FUTURE PROSPECTS

Currently, orbit determination for LRO is accomplished by utilizing Doppler and altimetric crossover data with an uncertainty in spacecraft positioning of only ≈ 12 m. By incorporating the high-precision LR measurements into this solution, the positioning accuracy is expected to improve, enabling more accurate orbital mapping products [2]. To facilitate the incorporation of the LR data into the orbit solutions, we are now focusing on the precise referencing of MET to TDB times. This shall be achieved by developing an improved clock model that includes effects of relativity as well as other effects. We expect that our clock calibration and referencing (MET to TDB) is more accurate than the standard conversions provided by the SCLK (Spacecraft Clock Kernel) [4]. Our data may enable improvements in orbit determination and gravity field modeling. While excellent gravity field data are available from the GRAIL mission [7], it will be interesting to analyze the benefits of the LR data. The accurate GRAIL fields provide a basis for quantitatively evaluating improvements in –pre-GRAIL models. Recently the same LR to LRO experiment with the existing facilities, hardware setups and the LOLA instrument have been used to successfully perform laser communication [8]. Thereby data transmission was achieved at a rate of 200 – 300 bit/s over a distance of ≈ 380000 km from a laser ranging station at GSFC to LRO in orbit around the moon. The regular range measurements from Earth to LRO could be used for data transmission by adjusting the time of arrival of a laser pulse within the LOLA range gate [8].

SUMMARY

We have received LR data from two successful passes from the Wettzell ground station and matched station laser fire and LOLA laser receive times. Also, a general matching capability was developed for automatic processing of large numbers of LR to LRO observation passes. The LR to LRO data that has been processed so far covers 1240 days, including data from commissioning phase until extended science mission 03 (approx. June 2009 - December 2012). RMS values are on average 13.2 cm for all participating stations. Currently a clock model capability is being developed for improving the referencing of MET to TDB by considering the influence of relativity as well as other effects. The derived LR data shall be used in orbit determination which will ultimately improve the accuracy of derived altimetric data products [cf. 2].

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